Probing the Dark Sector with Liquid Argon TPC Detectors

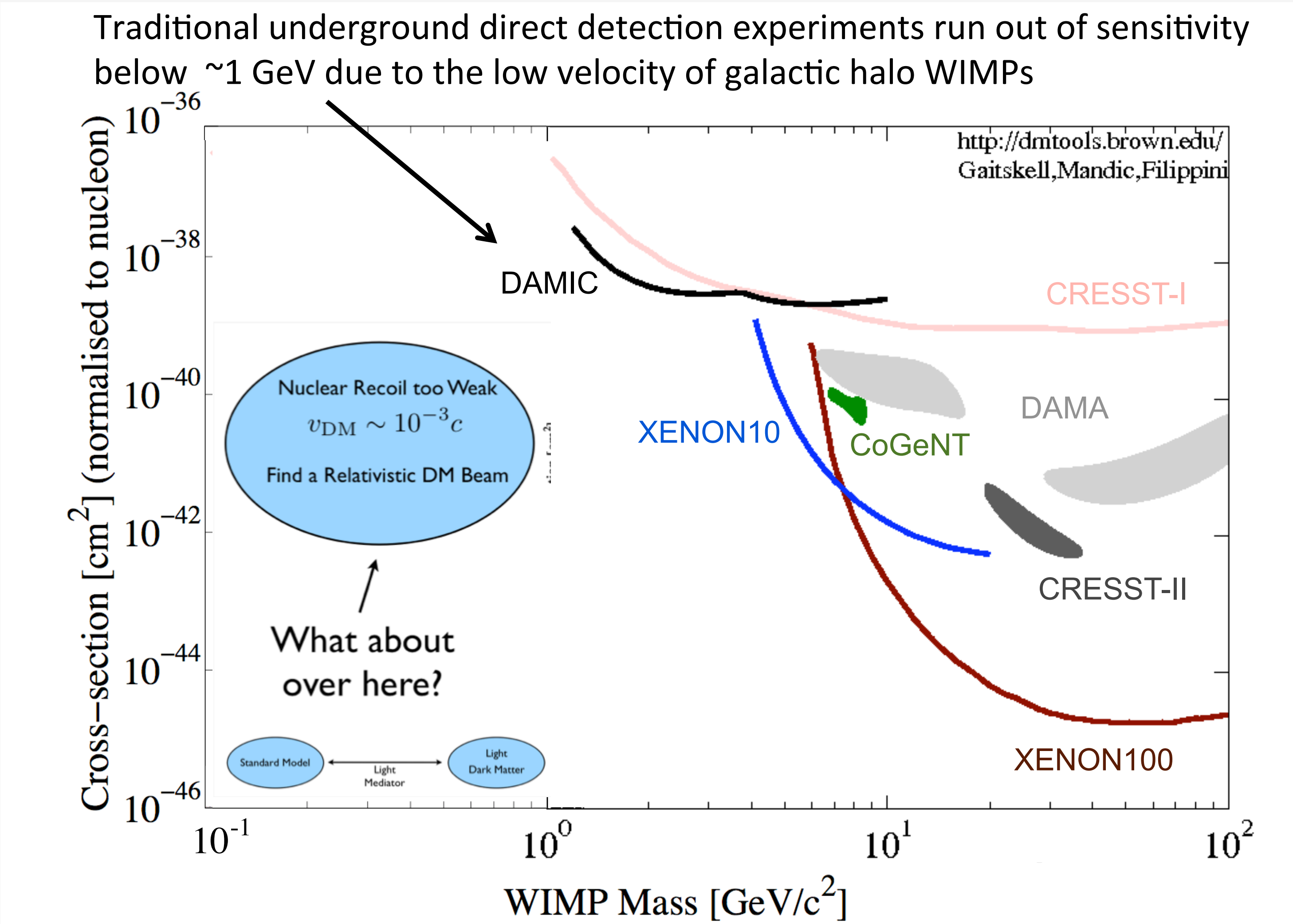
April 28, 2014

R. G. Van de Water (LANL)

Outline

- The case for light mass Dark Matter (<1 GeV) and how to produce them with protons beams.
- LAr-TPC technology and Dark Matter detection methods
- Dark Matter scattering sensitivities with MiniBooNE, MicroBooNE, and LAr1-ND.
- Methods to improve Dark Matter Sensitivities.
- Conclusions.

World Data on Low Mass Spin Independent WIMP Scattering



- Lee Weinberg limit (SM mediators W, Z) implies M_{wimp} >> 2GeV
- However, for low mass WIMPs you need a new mediator to produce the right relic density!

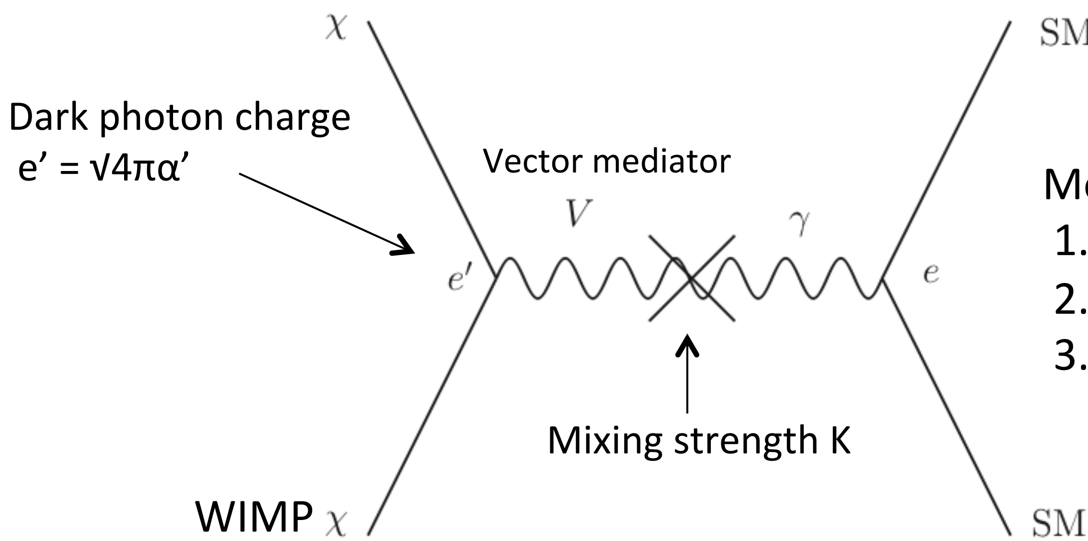
Minimal U(1) Dark Force Vector Portal Model

Opens up new annihilation channel for light WIMPs to achieve right relic density

B. Batell, M. Pospelov, A. Ritz Phys. Rev., vol. D80, p. 095024, (2009)

P. deNiveville, D. McKeen, A. Ritz, Phys.Rev.D86:035022 (2012)

$$\mathcal{L}_{\mathrm{DM}} = V_\mu \left(e\kappa J^\mu_{\mathrm{em}} + e' J^\mu_\chi \right) + \mathcal{L}_{\mathrm{kin}}(V, \chi) + \cdots$$



Model assumptions:

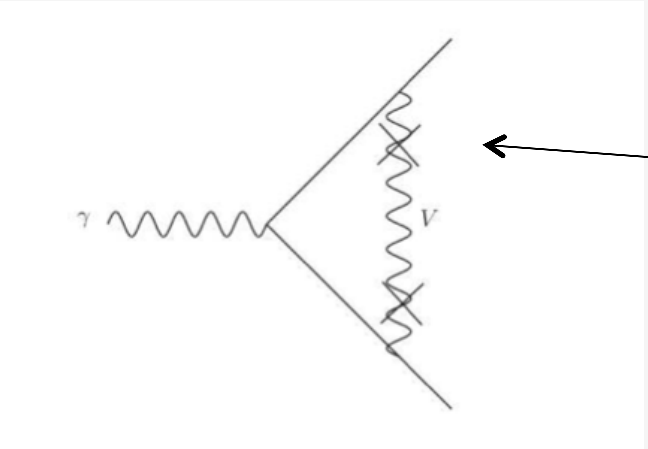
1. e = e' (perturbative regime)
2. K is small
3. $M_v > 2M_x$

Assuming thermal relic, if you know m_χ, m_V, κ, e'
you know the present DM density

This is just one of many possible portal interactions, e.g. sterile neutrino, scalar, Higgs, etc

Model Consequences for Muon g-2

- Light kinetically mixed vector V that serves as a mediator in this model also contributes to the anomalous magnetic moment of SM fermions.
- This can explain the muon g-2 discrepancy!

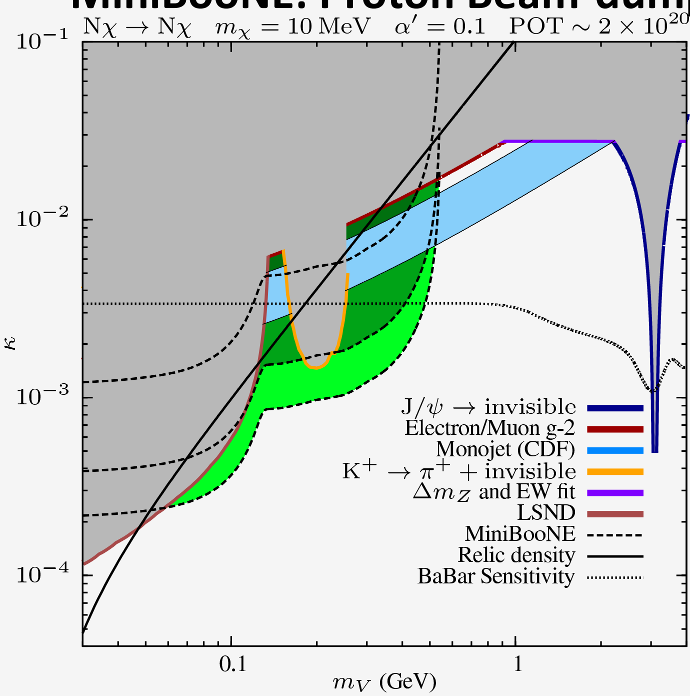


The crosses represent the kinetic mixing κ of the vector V with the photon

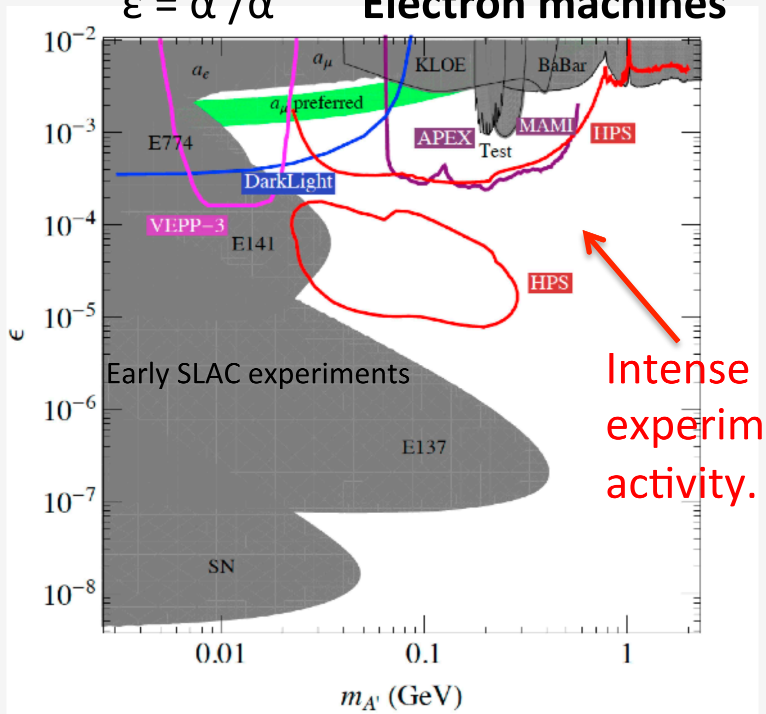
- These models are gaining attention as a possible explanation of the muon g-2 anomaly.

Two Regimes for Light Mass Dark Matter Models: We Need to Investigate both Regimes!

MiniBooNE: Proton Beam-dump



ε = α'/α Electron machines



Intense experimental activity.

$M_v > 2M_x$
Br(V -> SM) ~ $\kappa^2\alpha'/\alpha$
"Invisible V decay"

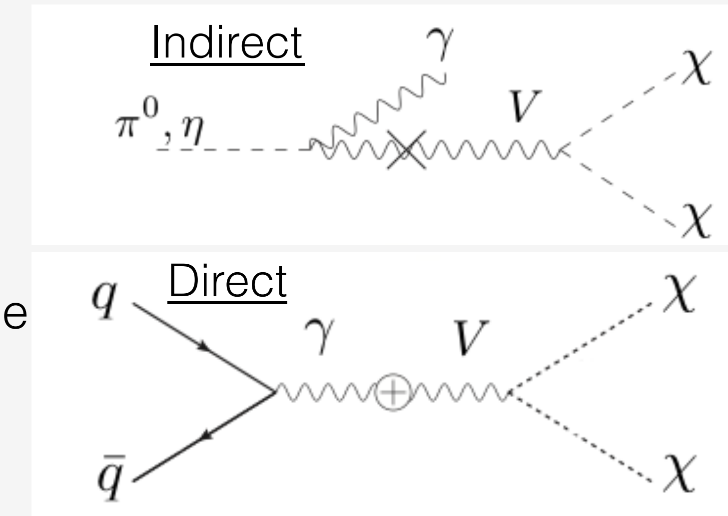
$M_v < 2M_x$
Br(V -> SM) ~ O(1)
"Visible V decay"

- Electron and Proton dump experiments compliment each other and extend the search for the hidden/dark sector!
- SNOMASS endorses proton beam-dump searches, and specifically MiniBooNE/MicoBooNE. These type of searches are detailed in the SNOMASS, LBNE, and Project X white papers.

Synergy with Intensity Frontier at Fermilab

Production:

- From proton-target interactions
- Requires intense beams with copious protons on target and variable energies (8 GeV, 120 GeV, etc)

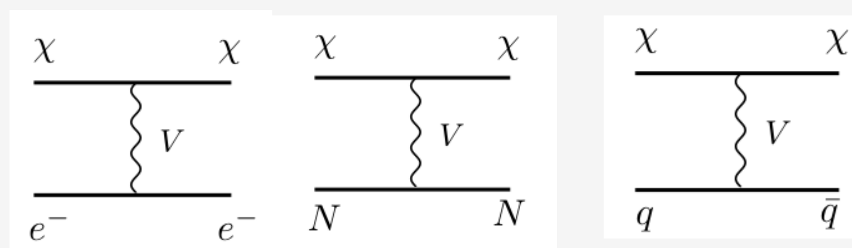


8 GeV

120 GeV for higher WIMP mass reach

Detection:

- Elastic scattering off of nucleons, electrons, or DIS
- Require near, large, sensitive, well-understood detectors

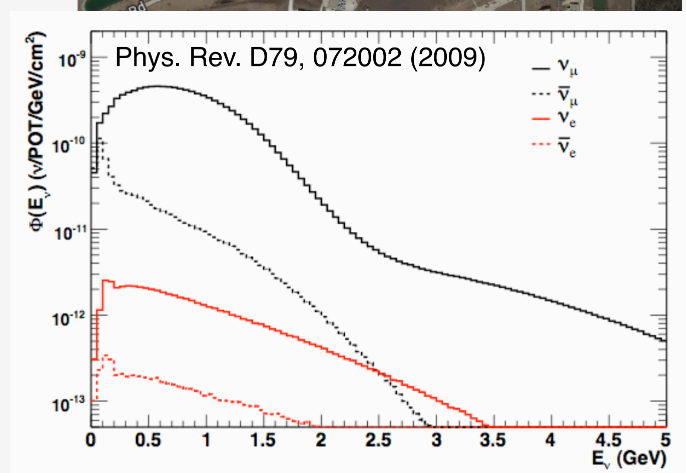


Neutrino sources and detectors are ideal for Dark Sector particle searches!

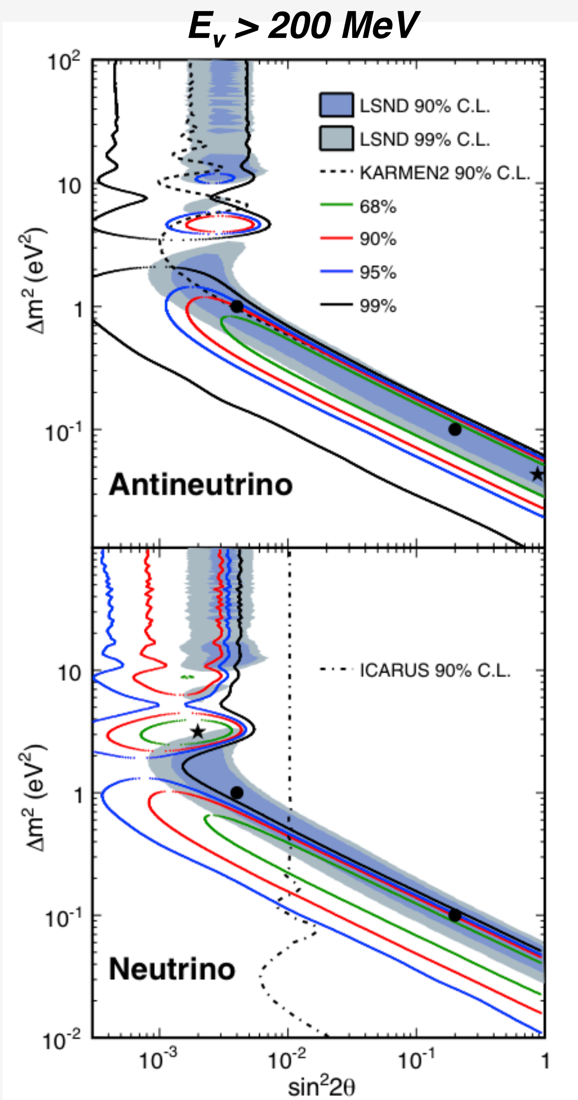
The Booster Neutrino Beamline (BNB) at Fermilab

- Neutrinos produced by protons from Booster accelerator
  - 8 GeV protons hit Be target
  - Neutrinos from decay of hadrons
    - 50 m decay pipe followed by ~450 m of dirt
    - Magnetic horn focus/defocus neutrino/antineutrino parents
    - Mostly produces muon neutrinos (or antineutrinos)

- **MiniBooNE:** 800 tons CH2 at 550 m
  - Ran 10 years neutrino and antinu mode.
  - Currently running beam-dump mode with 1E20POT already on tape, and aiming for another ~1E20POT.
- **MicroBooNE**: 87 tons LAr-TPC at 470 m
  - Under construction, starts later this year.
- **LAr1-NearDector**: 82 tons LAr-TPC at 100 m.
  - Proposed



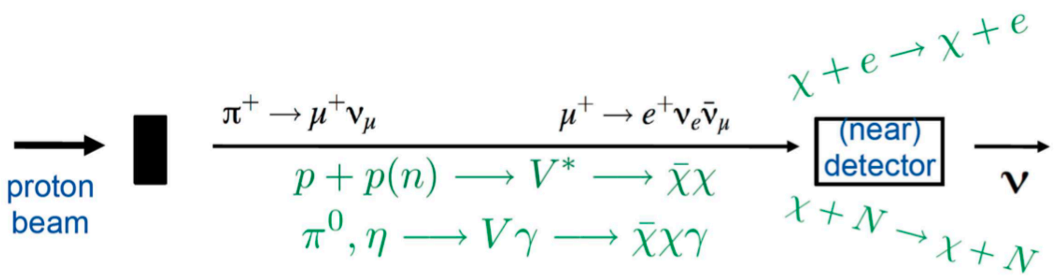
Why Study Neutrinos at the BNB?

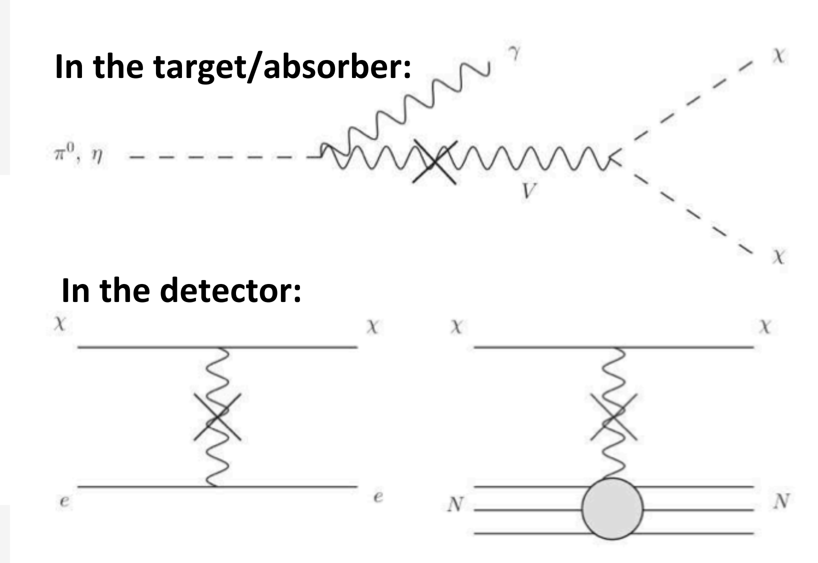


Phys. Rev. Lett. 110, 161801 (2013)

- LSND observation
  - LSND saw electron antineutrinos in beam of muon antineutrinos from stopped muons
  - Can be interpreted as neutrino oscillations, but with large Δm^2
- MiniBooNE results
  - Excess of electron neutrino and antineutrino appearance – consistent with LSND

Producing a Dark Matter Beam





Electron Elastic scattering

Nucleon Elastic scattering

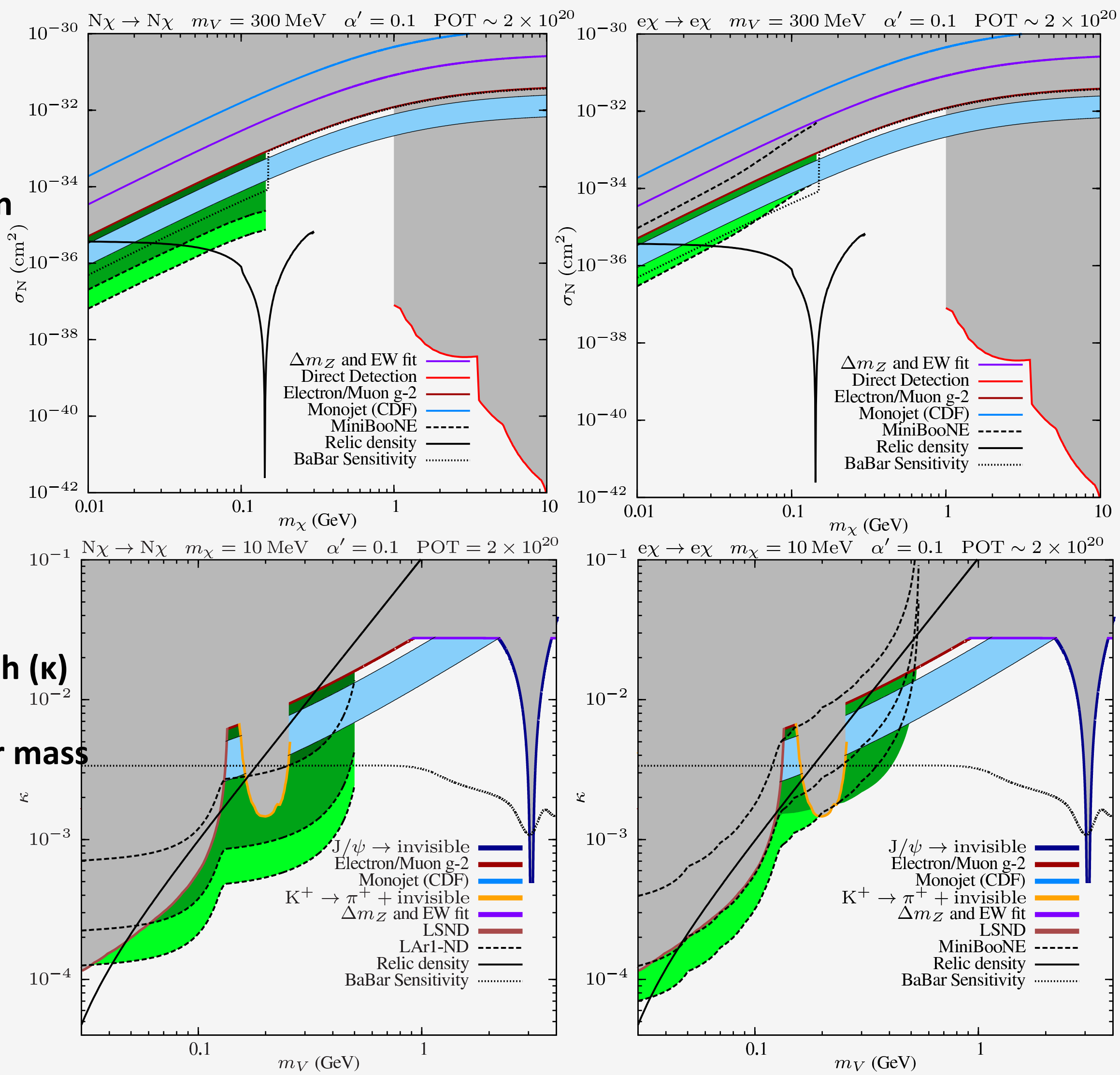
- Monte Carlo Simulation of WIMP Production at MiniBooNE/MicroBooNE:
  - Use HARP-MiniBooNE Be target Sanford-Wang meson production model.
  - π^0 and η production errors ~25%.
- Electrons and nucleon can be reconstructed in MiniBooNE with ~35% efficiency. For LAr-TPC assume 70%.
  - MiniBooNE Nucleon (Electron) systematic errors 20% (12%).
  - Working on similar estimates for LAr-TPC.
  - **Low energy (<200 MeV) regime is important.**
  - Nucleon xsection scattering larger due to center of mass energy scaling $\sigma \sim E_{cm}$

MiniBooNE Dark Matter Sensitivities

DM-Nucleon Scattering | DM-Electron Scattering

DM cross section vs DM mass

Mixing strength (κ) vs Vector mediator mass



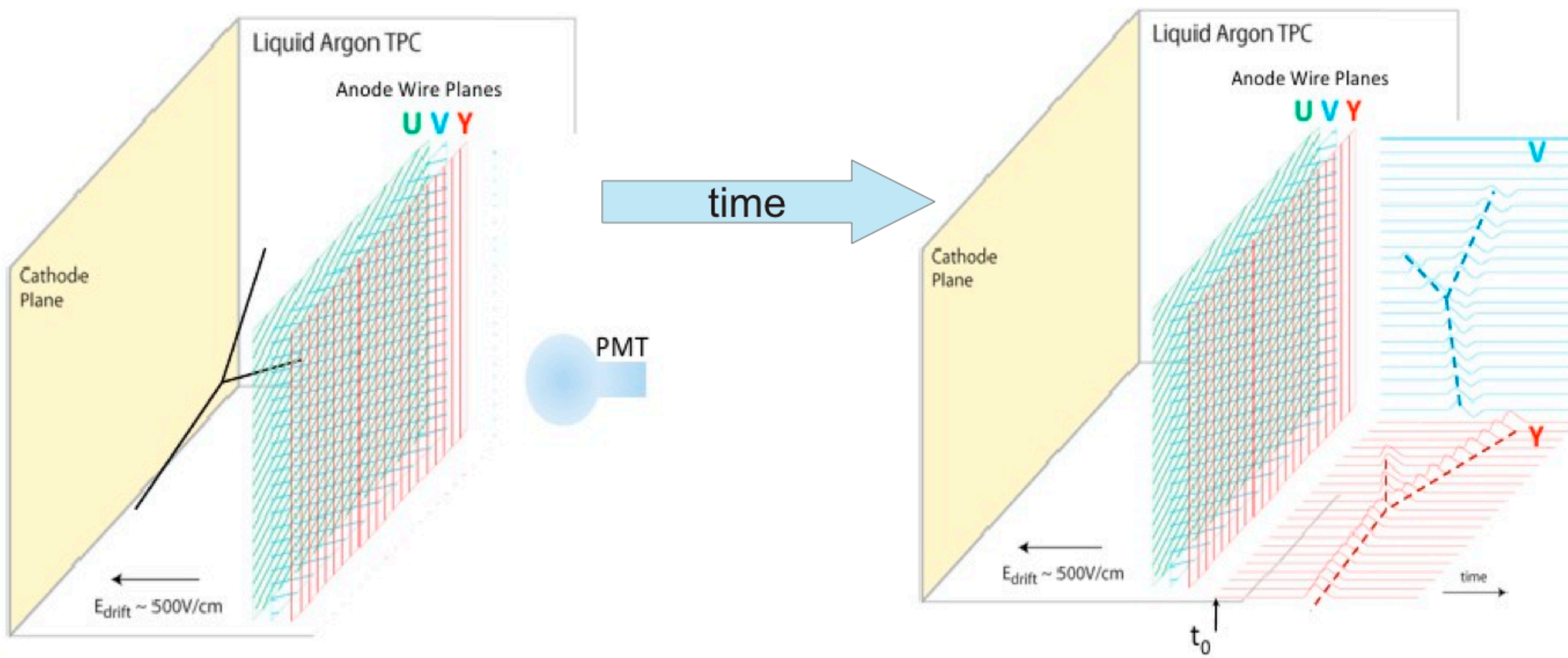
- Number of DM events detected in MiniBooNE:
  - -Dark Green: >1000
  - -Green: 10-1000
  - -Light Green: 1-10
- What sensitivity can MB actually achieve?
- $2M_x < M_v$ and sensible choice of model parameters M_x, M_v, κ, α'.
- Nucleon cross sections larger than electrons.
- Light blue band is muon g-2 signal.
- **Solid black line is Dark Matter relic density limits**

What can LAr-TPC Detectors add to these Searches?

- LAr TPC has much better track spatial resolution, background rejection, and signal efficiency than mineral oil detectors.
- This allows detailed event reconstruction that can separate electron from photon signals.
  - This is crucial to address the MiniBooNE oscillation signal.
- These improvements will also help at low energy to reconstruct nucleons and electrons for DM searches, where much of the DM signal resides.

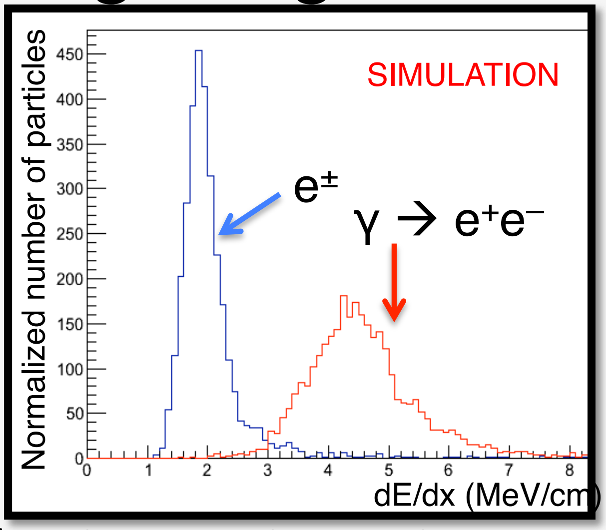
How a LAr TPC Works

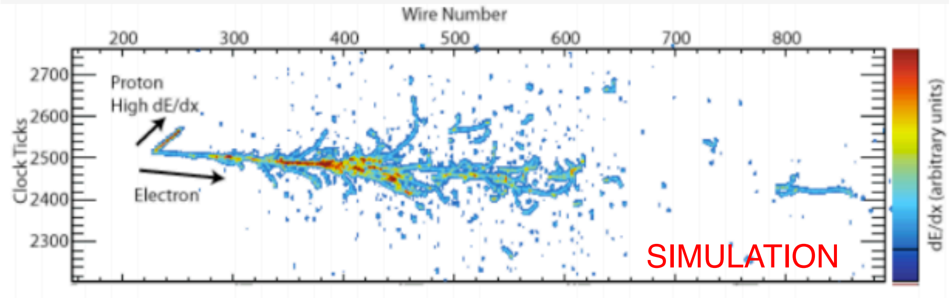
- Charged particles in argon create electron-ion pairs and scintillation light.
- Electrons are drifted towards the anode wires.
- Multiple anode planes together with drift time allow 3D reconstruction.
- Collected charge allows calorimetric reconstruction.

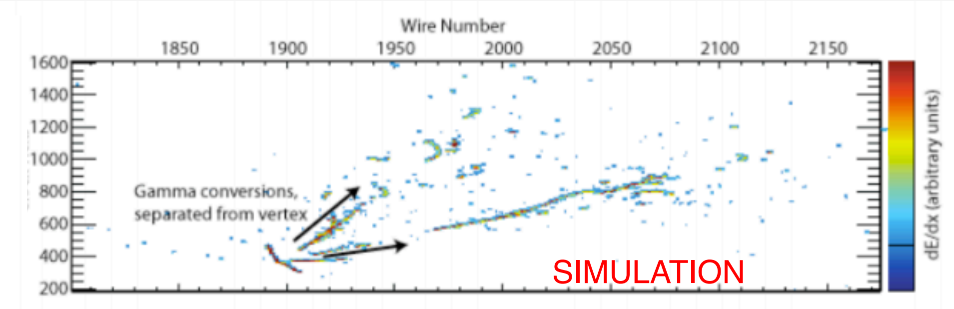


LArTPCs to the rescue!

- LArTPCs offer window into very beginning of electromagnetic shower:
  - Measure dE/dx
    - Low? single electron
    - High? electron-positron pair from converted photon
  - Measure displacement from neutrino interaction point
    - No displacement? particle produced at interaction point.
    - Some displacement? decay from neutral particle

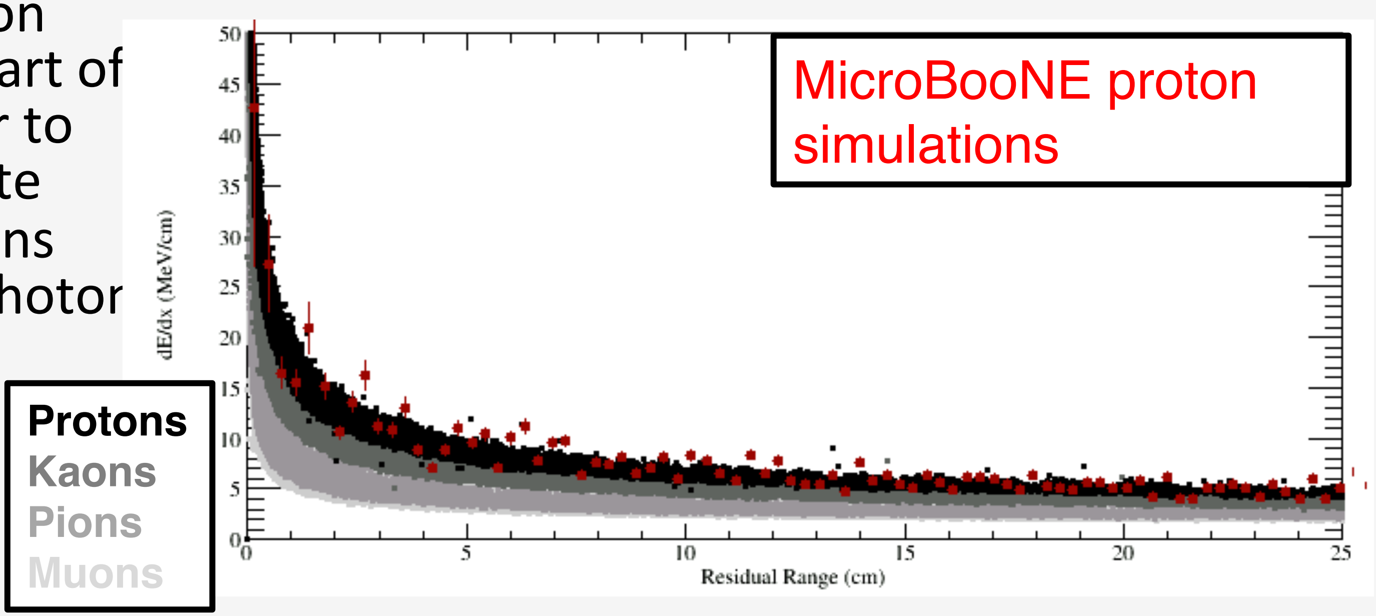






Particle Identification

- Topological discrimination
  - Separate track- and shower-like objects based on hit distribution
  - Charged pions vs. muons?
- The real workhorse: dE/dx
  - Discriminate between protons, kaons, and pions/muons
  - Focus on early part of shower to separate electrons from photor



- Can reconstruct/identify protons down to 20 MeV

The MicroBooNE Cryostat

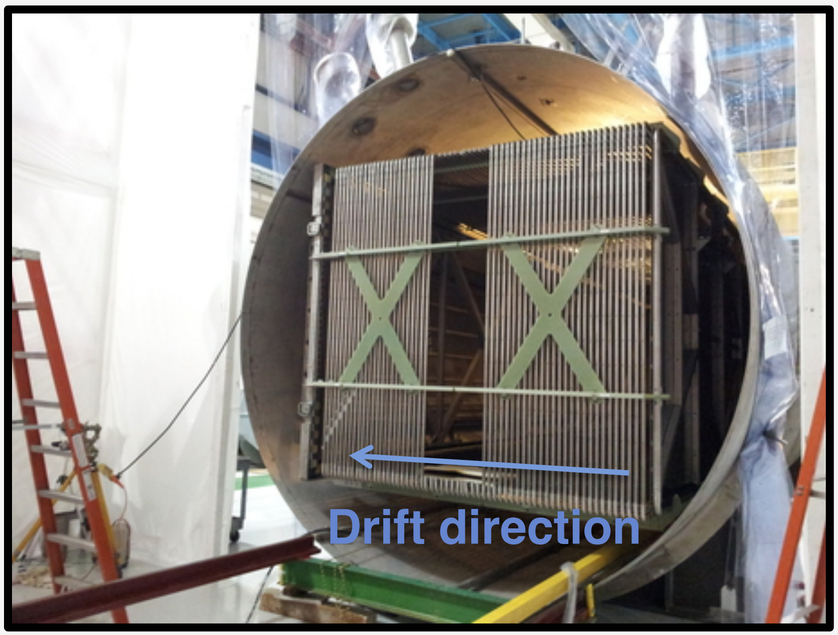
- 3.5 m diameter steel cylinder
- Holds 170 tons of liquid argon
- Foam insulation after installation in new LAr Test Facility building

Platform will be removed during installation

Cryostat will be lowered into pit of building

The MicroBooNE TPC

- TPC is rectangular in shape
  - 2.33 m high and 10.37 m long with a 2.56 m drift length
  - → 1.6 ms drift time from cathode to anode
  - Active volume ~80 tons; expected fiducial volume ~60 tons



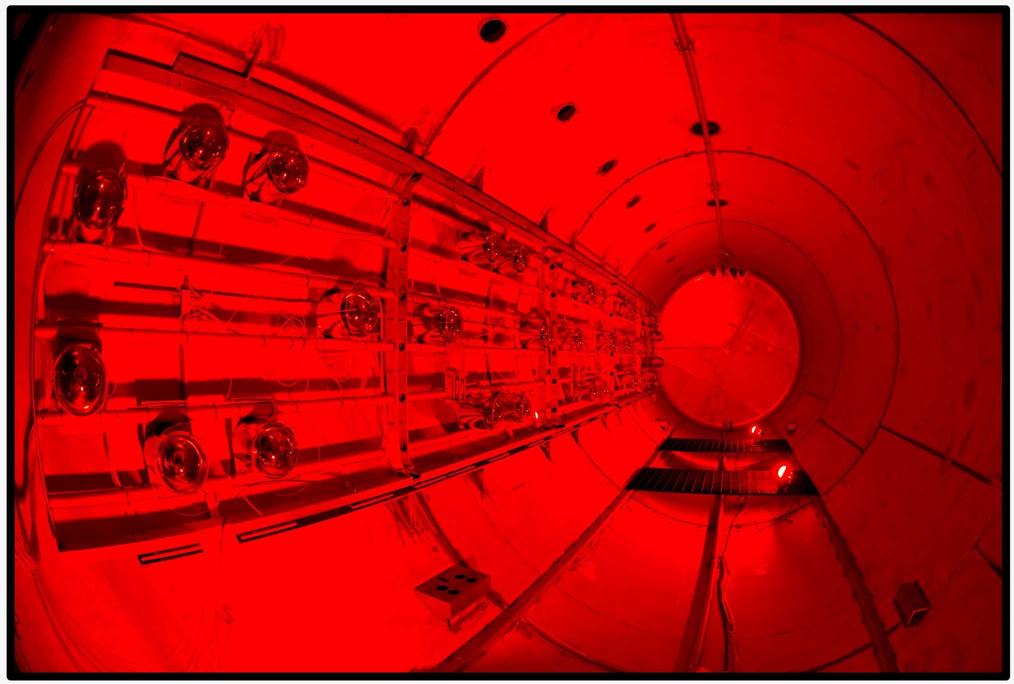
Field shaping tubes

- Stainless steel tubes maintain constant electric field gradient (nominal 500 V/cm) along drift length
- Supported by insulating G10 braces

MicroBooNE's photo-detection system

- Array of 32 PMTs sit behind the TPC wires
  - TPB-coated acrylic plates wavelength shift 128-nm light
  - Two gain settings

- PMTs provide important timing information
  - Precise "t_0" for start of electron drift
  - Time and position of out-of-time ionization
    - Cosmic ray overlap



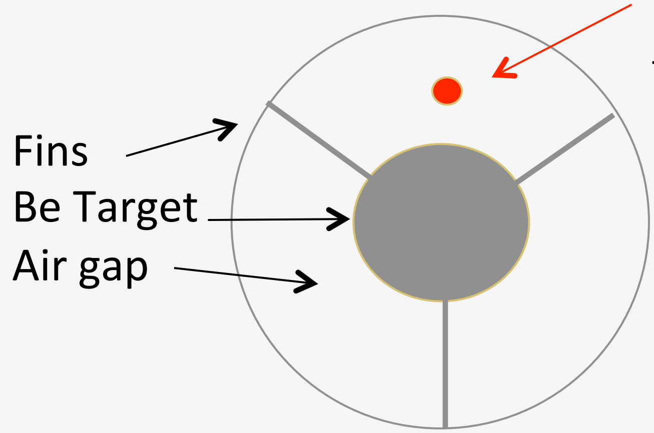
Enhancing the Dark Matter Search at the BNB

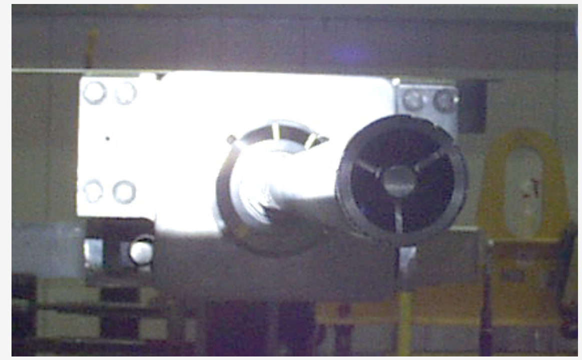
- The Dark Matter scattering signal looks like neutrino nucleon or neutrino electron elastic scattering. Thus, neutrino interactions are the biggest background to these searches.
  - In MB ~100,000 NC-elastic events
  - In MicroBooNE ~20,000 NC-elastic events
  - In LAr1-ND, ~113,000 NC-elastic events (2E20 POT)
- We can employ a beam dump type method to significantly reduce charged meson decay, and hence the neutrino flux (Flux reduction ~1/44)

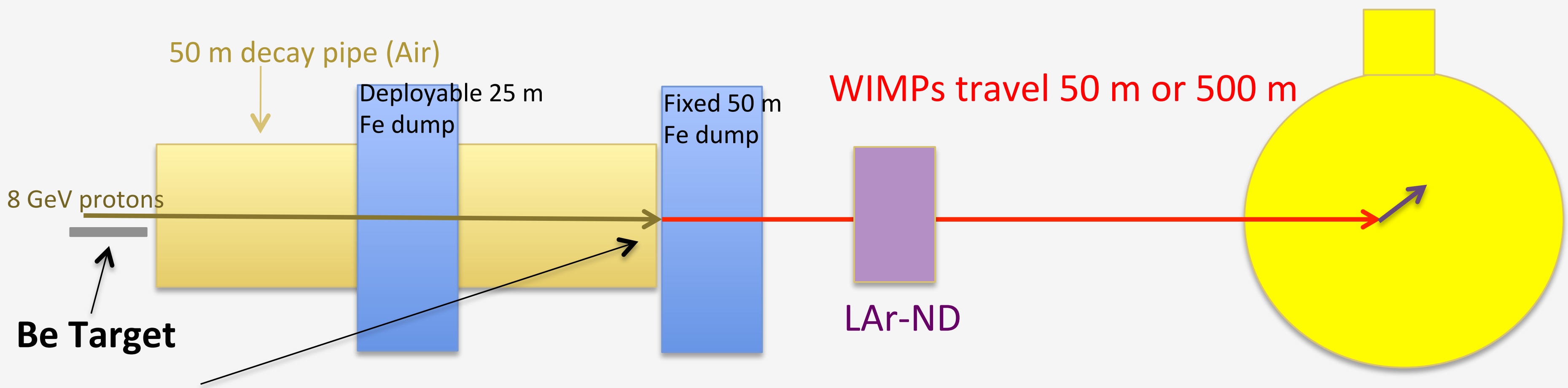
Beam Dump Running: A Unique Capability of the BNB

- Beam spot position in beam off target mode (~1 mm spread).
- Target is 1cm diameter, with 1cm air gap

BNB has the capability to steer the protons past the target and onto the 25m or 50m iron dump







- π^0 and η produced by protons in the iron quickly decay producing DM (χ)
- Charged mesons are absorbed in the iron before decaying, which significantly reduces the neutrino flux (still some production from proton-Air interactions). **Neutrino Flux reduced by a factor of 44+/-3 with 50m dump.**

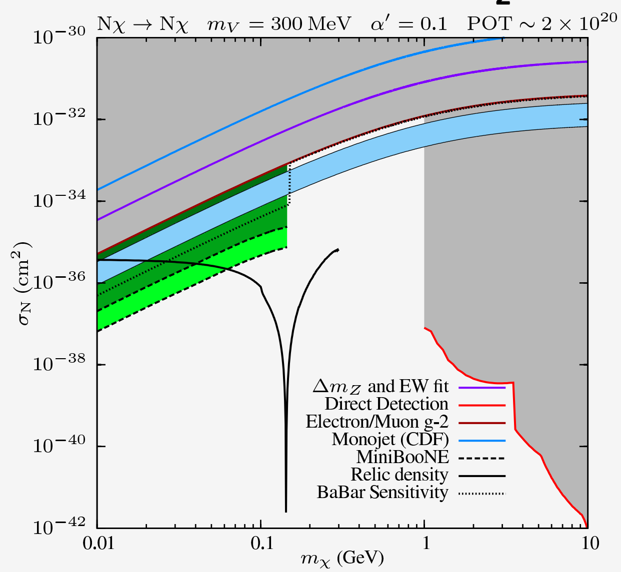
DM Scattering Signal Comparisons

	MiniBooNE	MicroBooNE	LAr-ND
Beam off Target Run	2E20POT, 50m dump	2E20POT, 50m dump	2E20POT, 50m dump
Distance from 50m Dump (m)	500	420	50
Analysis Fiducial Mass (tons)	450	61	40
Efficiency (nucleon or electron)	30%	60%	60%
Approximate scaling (*)	1.0	0.38	17.7
DM-nucleon signal (**)	**1326**	**503**	**23500**
ν-nucleon background (***)	406+/-80	40	2500
DM-electron signal (**)	**4.8**	**1.8**	**85.0**
ν-electron background (***)	~0.6	< 0.1	~10

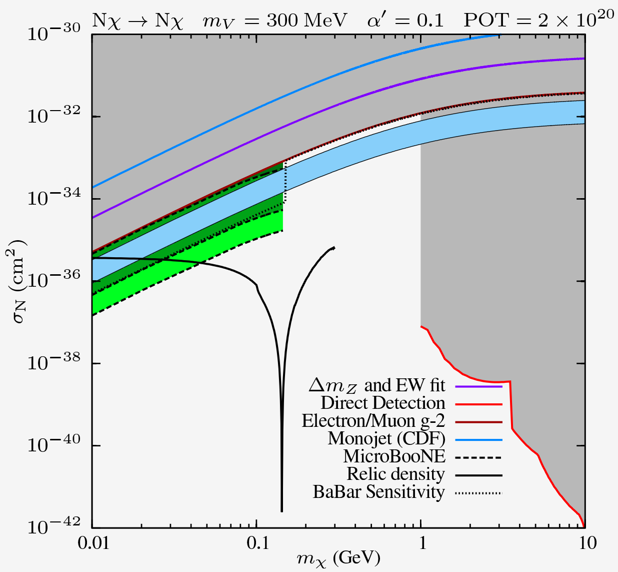
- (*) Sensitivity plots include other signal scaling factors, e.g. non $1/r^2$ scaling, energy, etc.
- (**) Assume signal point M_x= 50MeV and xsection= $8E10^{-36}$ cm^2.
- (***) BeamDump factor 1/44, POT, efficiency, and electron scatter cut $\cos\theta_{beam} > 0.98$.

Signal Sensitivities for DM-NUCLEON Scattering (2E20 POT)
Cross Section vs. Dark Matter Mass

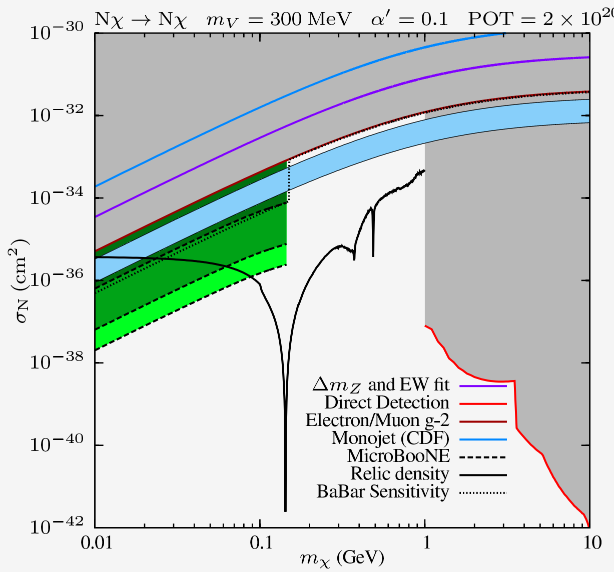
MiniBooNE-CH_2



MicroBooNE-LAr



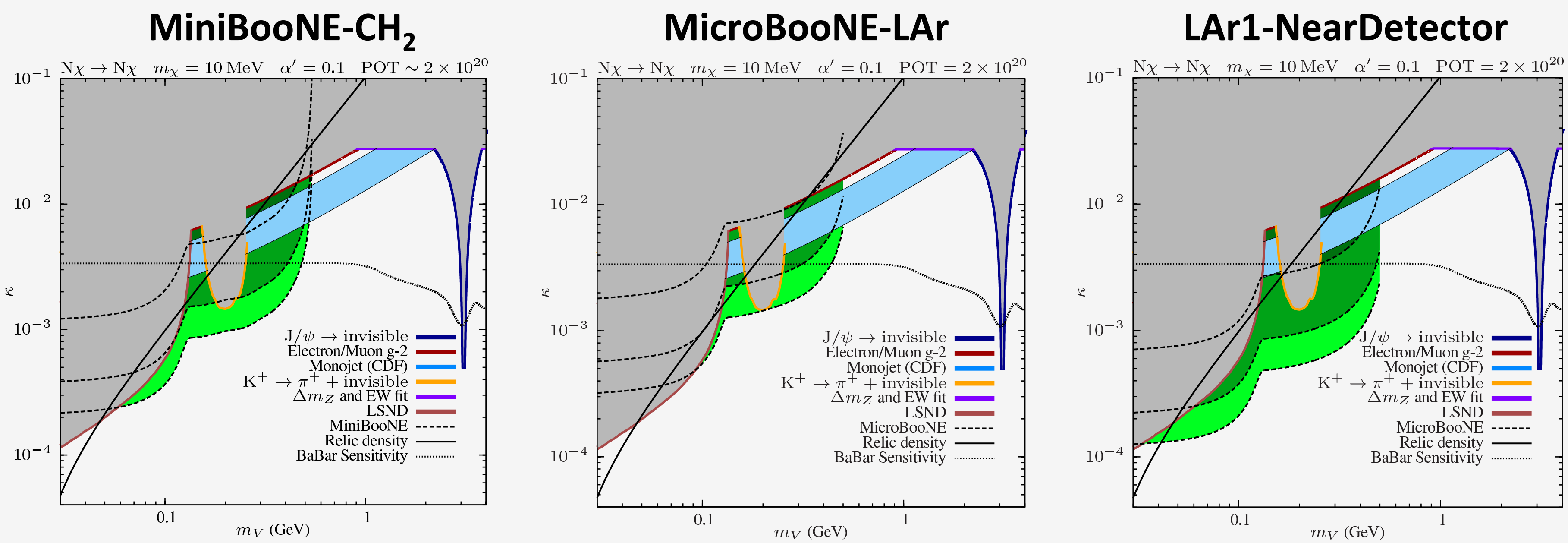
LAr1-NearDetector



- Signal events: Dark Green > 1000; Green: 10-1000; Light Green: 1-10
- These are signal sensitivity plots. Actual measurement sensitivities/limits will depend on background rates and systematic errors.

These and following plots are for reasonable choices of M_x, M_v, and α' = 0.1
Use of similar parameter values allow comparisons of different experiments.

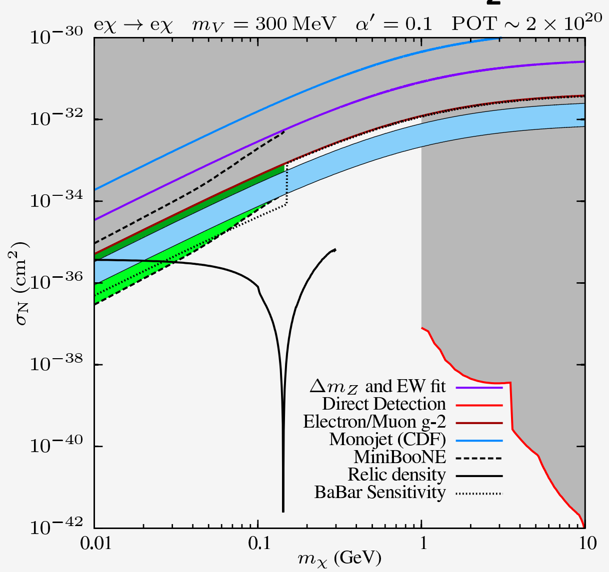
Signal Sensitivities for DM-NUCLEON Scattering (2E20 POT)
Mixing Strength vs. Vector Mediator Mass



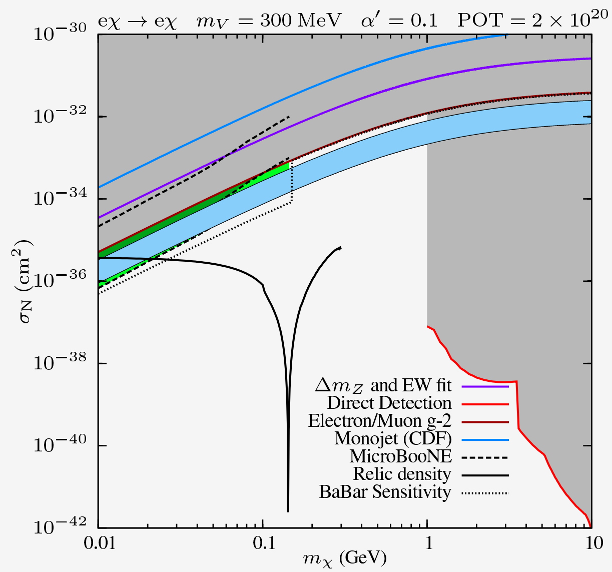
- Signal events: Dark Green > 1000; Green: 10-1000; Light Green: 1-10
- These are signal sensitivity plots. Actual measurement sensitivities/limits will depend on background rates and systematic errors.

Signal Sensitivities for DM-ELECTRON Scattering (2E20 POT)
Cross Section vs. Dark Matter Mass

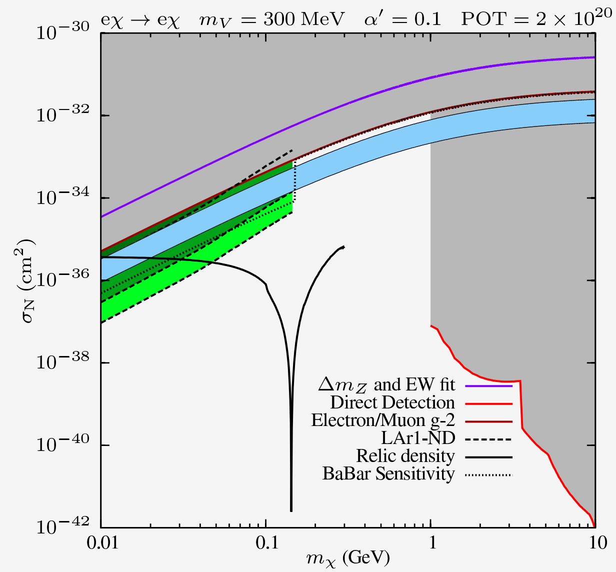
MiniBooNE-CH_2



MicroBooNE-LAr



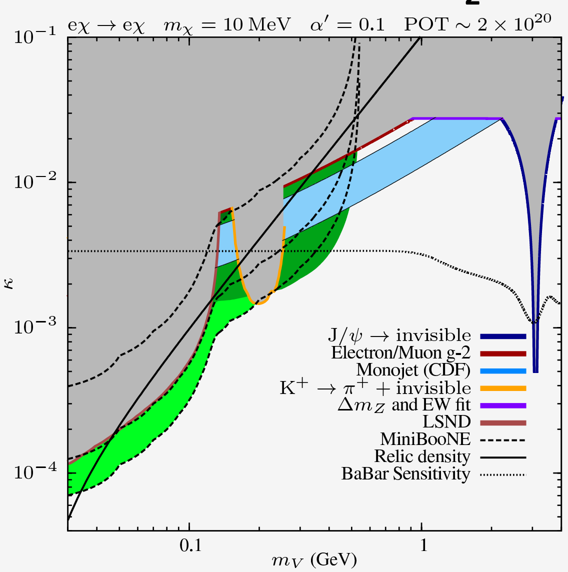
LAr1-NearDetector



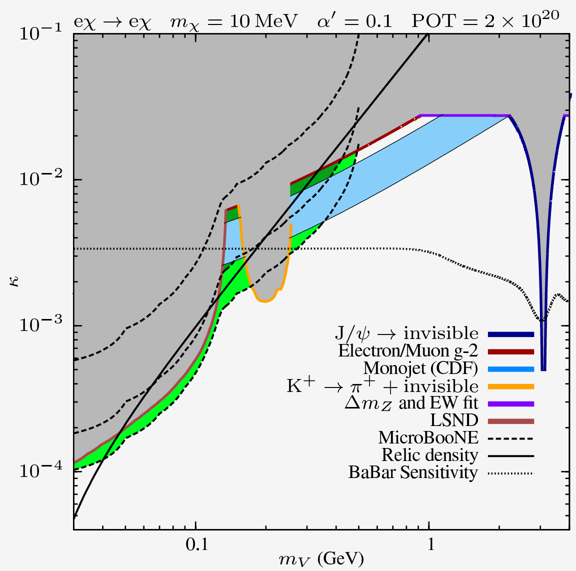
- Signal events: Dark Green > 1000; Green: 10-1000; Light Green: 1-10
- These are signal sensitivity plots. Actual measurement sensitivities/limits will depend on background rates and systematic errors.
- Electron signal sensitivity down due to lower cross sections. However, using direction information will significantly improve measurement sensitivity

Signal Sensitivities for DM-ELECTRON Scattering (2E20 POT)
Mixing Strength vs. Vector Mediator Mass

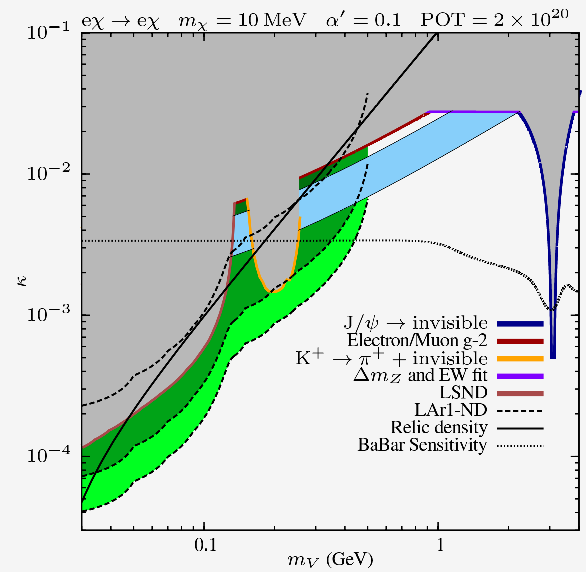
MiniBooNE-CH_2



MicroBooNE-LAr



LAr1-NearDetector



- Signal events: Dark Green > 1000; Green: 10-1000; Light Green: 1-10
- These are signal sensitivity plots. Actual measurement sensitivities/limits will depend on background rates and systematic errors.

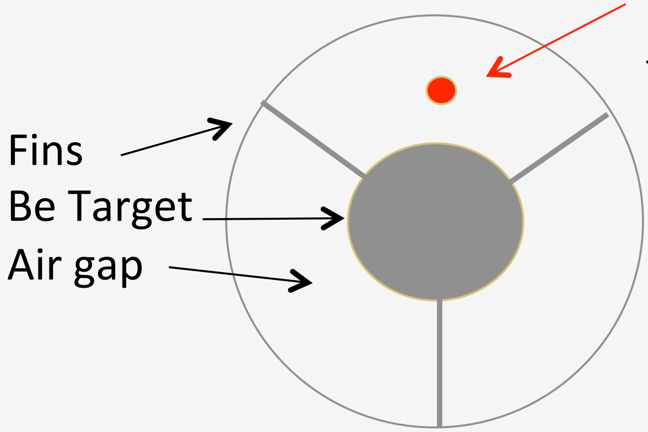
Methods to Enhance DM Searches

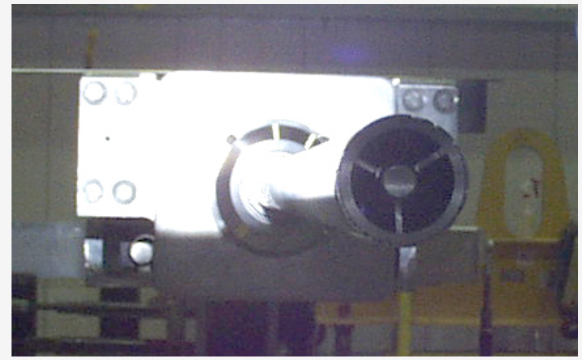
- Beam-Dump running
  - Primary method to reduce neutrino backgrounds.
- Nucleon recoil energy fits/cuts.
  - Both MB (5 - 10%) and LAr (< 5%) have good energy resolution.
- Beam angle fits/cuts
  - Both MB and LAr have good direction resolution < 3^0
- Event time of flight relative to beam
  - MB has ~nsec time resolution. LAr TPC ~msec, however photon detection system will significantly improve LAr event timing.

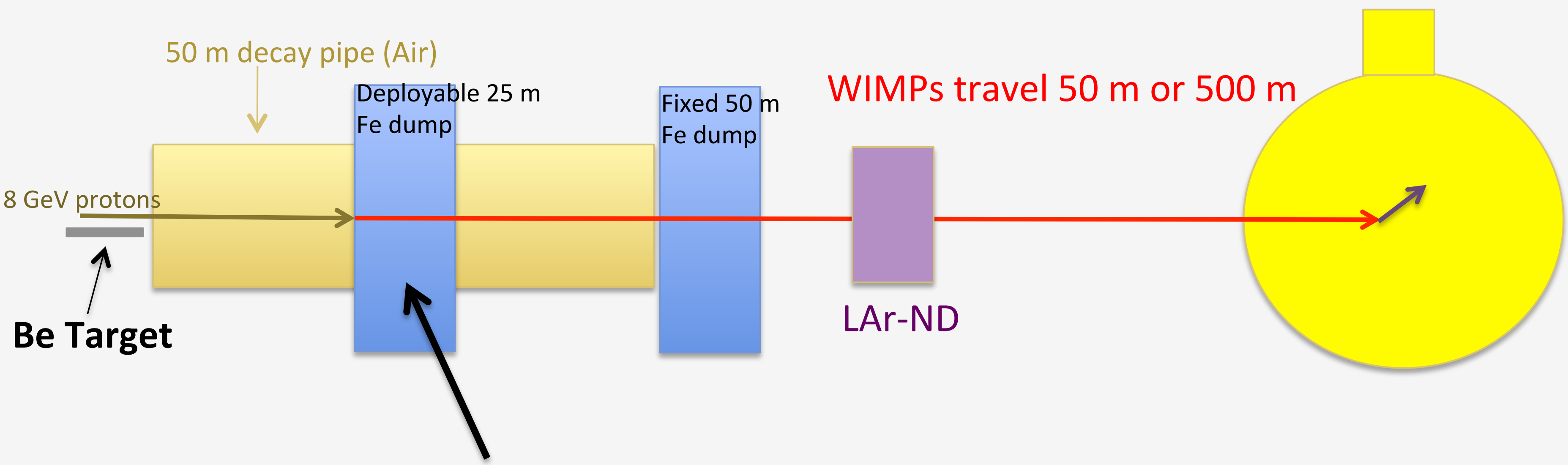
Beam Dump Running: A Unique Capability of the BNB

- Beam spot position in beam off target mode (~1 mm spread).
- Target is 1cm diameter, with 1cm air gap

BNB has the capability to steer the protons past the target and onto the 25m or 50m iron dump

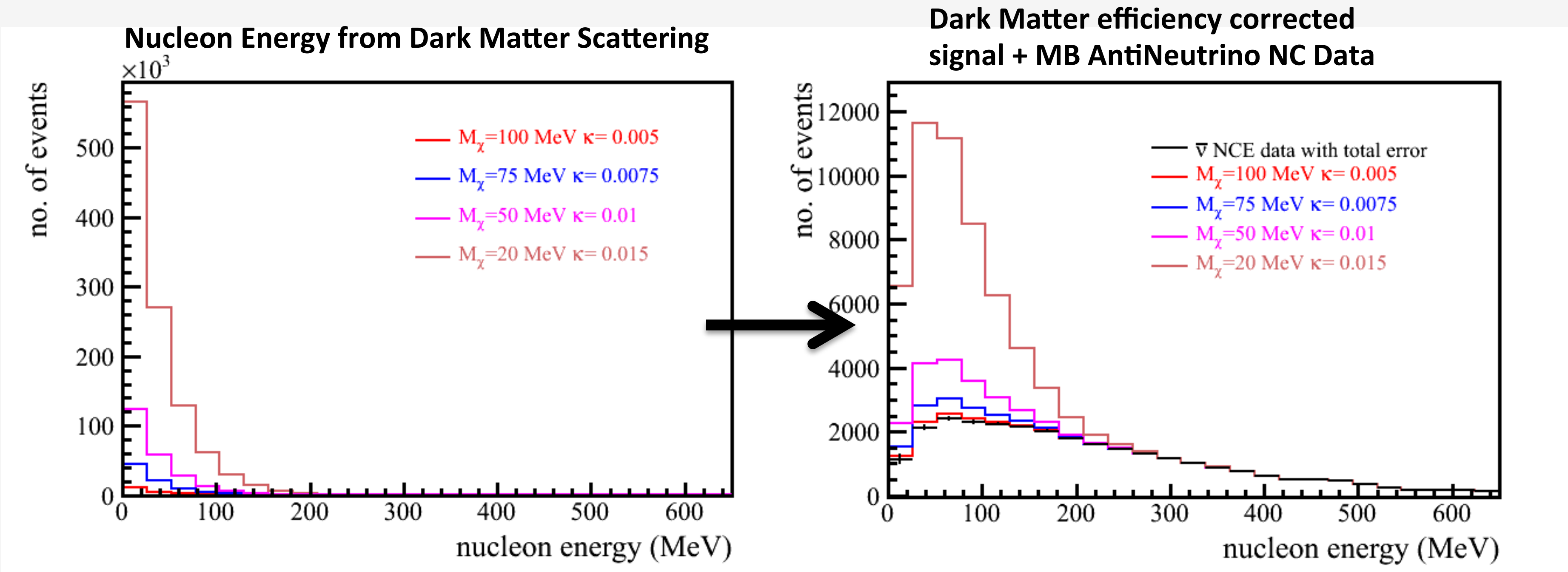






- **During a dedicated MicroBooNE/LAr1-ND deploying the 25m dump would decrease neutrino backgrounds by a factor of ~2 (1/88 flux reduction).**

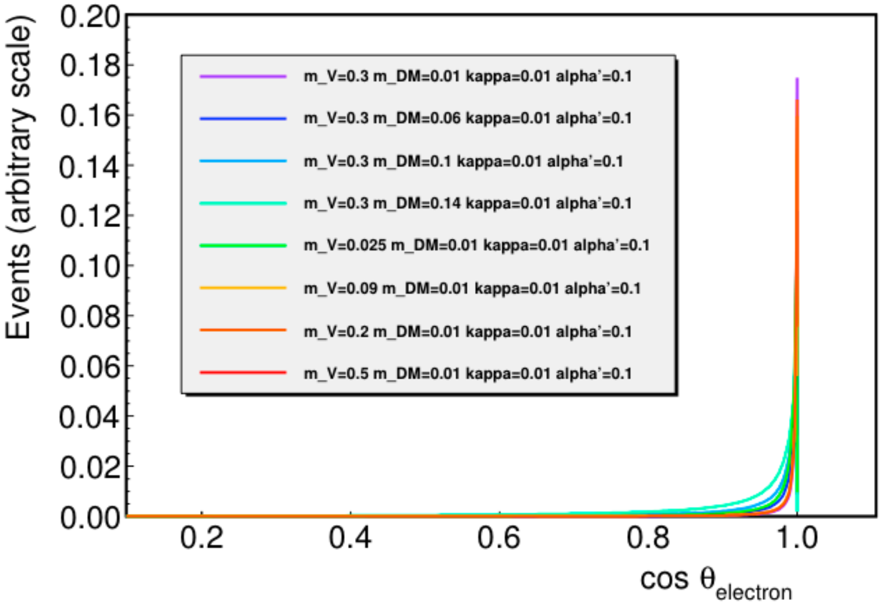
Dark Matter-Nucleon Scattering Energy

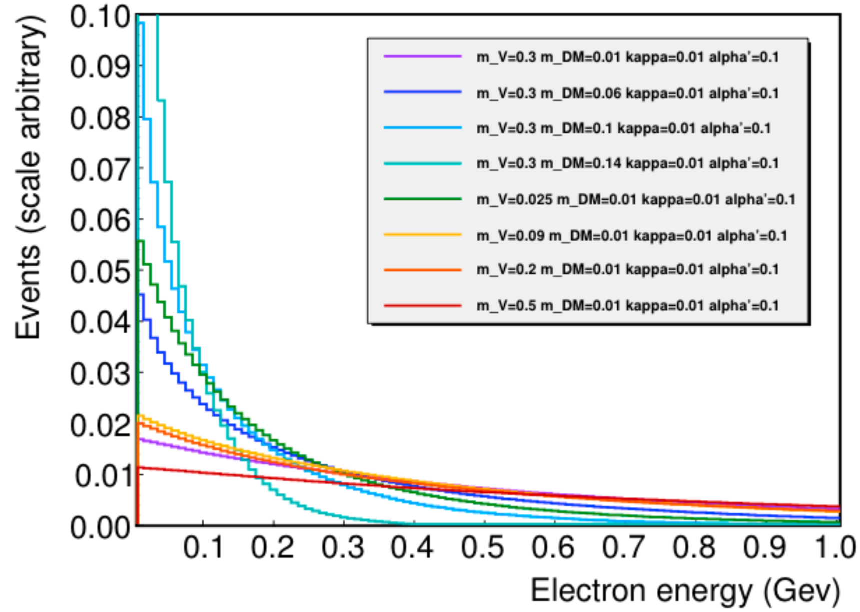


- For different model parameters, the dark matter signal is below 250 MeV nucleon energy.
- MiniBooNE signal falls off rapidly below 40 MeV due to detector reconstruction efficiency.
- **LAr-TPC proton reconstruction threshold will be better ~20 MeV. However, backgrounds (cosmics/dirt) are a bigger issue!**

DM-Electron channel could be much more sensitive despite lower signal rate

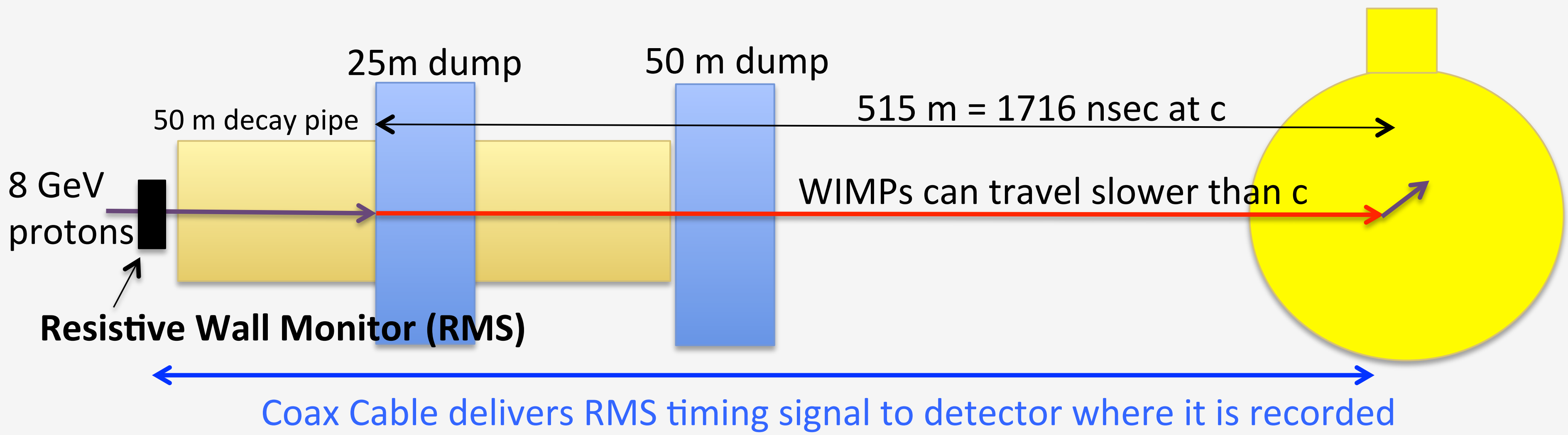
- DM-electron and ν-electron elastic (ES) scattering forward peaked.
- CC and NC neutrino scattering ~isotropic in angle wrt beam direction.
- $Cos\theta_{beam}$ > 0.98 cut reduces backgrounds by x100

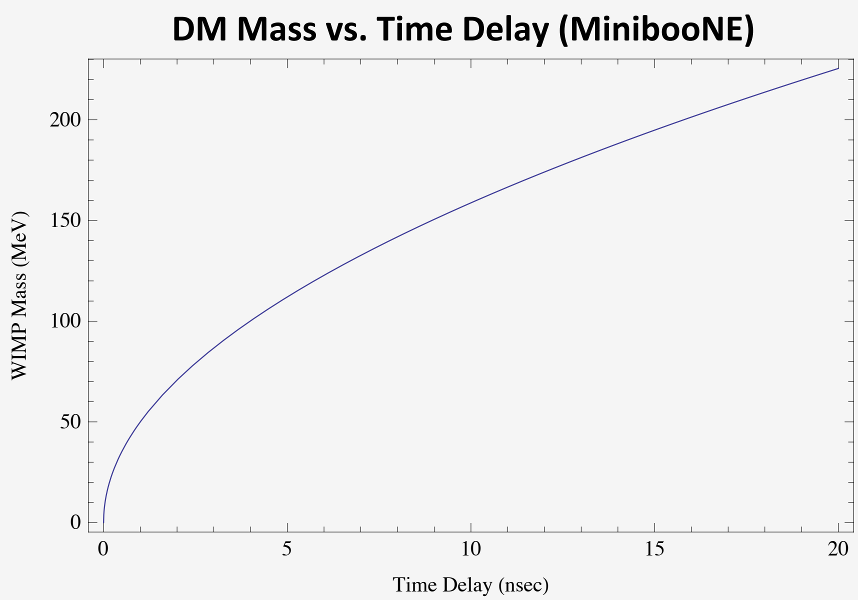




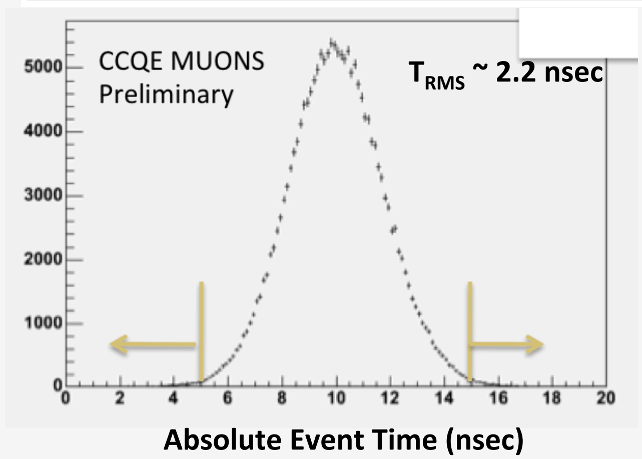
- **Electron channel could be most sensitive channel due to low backgrounds and systematic errors, especially in neutrino mode.**

Dark Matter Time of Flight: Will it work for LAr??



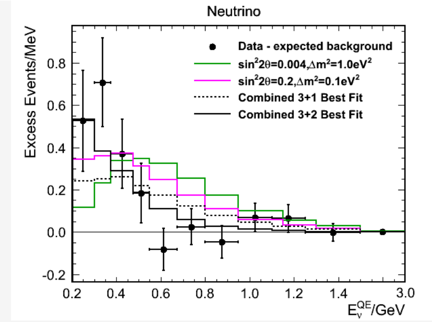


Timing cut (nsec)	Background Reduction (%)	WIMP Velocity β	WIMP Mass (MeV)
3.0	90	0.9984	85
4.6	99	0.9974	108
5.9	99.9	0.9967	122



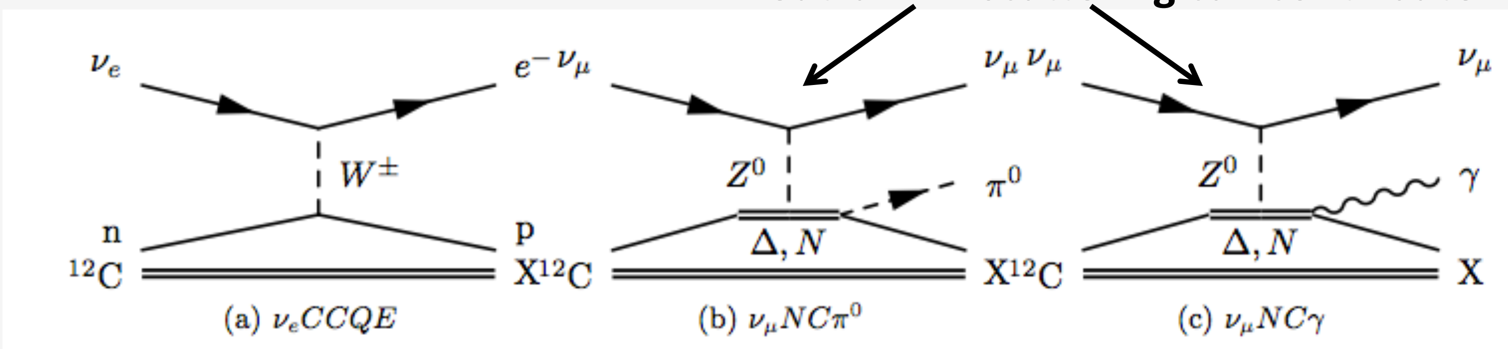
-Electrons timing will be similar to muons, while NC nucleon events twice as worse.

Testing the MB low Energy Excess, Something to Consider…



- Just like neutrino-NC scattering, Dark Matter-NC scattering also produces copious amounts of Δ decays.

Neutral DM scattering can contribute



- If MicroBooNE observers the MB low energy excess to be photons, this does not prove all, or part, of the low energy excess is entirely standard model processes.
  - A 2E20POT beam-dump run could add valuable information about the source of photons, i.e. **SM photon processes should vanish.**
  - Beam-dump running in general is a useful systematic check.

Conclusions

- LAr technology has advantages such as event reconstruction, background rejection, lower systematic errors, energy reconstruction, etc, which will enhance Dark Matter searches.
- Due to its proximity to the dump, LAr1-ND has significantly better Dark Matter signal sensitivity than MB and MicroBooNE.
- Kinetic Mixing (Dark Sector) Models have recently gained attention to explain muon g-2 anomaly
    - Searches with the BNB + MB and LAr-TPC can test g-2 region.
- The technique of exploiting proton beam-dump experiments for Dark Sector searches has been highlighted at SNOMASS.
    - MiniBooNE Beam-Dump proposal accepted and currently running. Lessons learned from run will help to motivate and guide searches with future LAr detectors on the BNB.
        - **Motivate MicroBooNE/LAr1-ND beam-dump run with 25m absorber.**
    - If MB observes a signal, then MicroBooNE/LAr1-ND could quickly verify/refute the signal with different systematics.

BackUp Slides